

Torrefied versus conventional pellet production – A comparative study on energy and emission balance based on pilot-plant data and EU sustainability criteria



D. Agar^{a,b,*}, J. Gil^c, D. Sanchez^c, I. Echeverria^c, M. Wihersaari^d

^a Department of Chemistry, University of Jyväskylä, P.O. Box 35, 40014 Jyväskylä, Finland

^b Process Chemistry Centre, Åbo Akademi University, Piispankatu 8, FI-20500 Turku, Finland

^c National Renewable Energy Centre (CENER), C/Ciudad de la Innovación 7, 31621 Sarriguren, Navarra, Spain

^d Department of Chemical Engineering, Åbo Akademi University, P.O. Box 311, 65101 Vaasa, Finland

HIGHLIGHTS

- Presents pilot-scale torrefaction data using rotary-drum reactor.
- CO₂ emissions and energy balance of torrefied vs. conventional pellet production.
- EU sustainability criteria methodology (RED) used in calculations.
- Torrefied pellets CO₂ emissions 45 g MJ⁻¹ with 77% emission savings in co-firing.
- Torrefied and conventional pellets generate similar CO₂ emissions.

ARTICLE INFO

Article history:

Received 6 February 2014

Received in revised form 1 August 2014

Accepted 4 August 2014

Available online 4 September 2014

Keywords:

Torrefaction
Environmental impact
Emissions
Wood pellets
Co-firing
RED

ABSTRACT

Torrefaction is an emerging technology which enables greater co-firing rates of biomass with coal. To date however there has been a lack of real production data from pilot-scale torrefaction plants. Without such data any environmental benefits of torrefied pellet production are difficult to quantify.

In this study data on consumable inputs from a semi-industrial torrefaction plant and the physical properties of produced pellets are used to analyse energy input and air emissions of torrefied pellet production and product transport. EU sustainability criteria are used to compare CO₂-equivalent emissions from torrefied and conventional pellet production starting from harvesting of logging residues to end use of co-firing the pellets with coal. A production scenario is examined in which raw material supply and production takes place in Finland with co-firing in Spain. The influence of transport distance (by lorry, rail and ship) on environmental impact is analysed for European and representative North American production sites.

Results indicate about 4.5 GJ of energy is consumed for each tonne of torrefied pellets compared to 3.3 GJ for conventional pellets; representing 23% and 21% of the energy content of the pellets respectively. If electricity from renewable sources can be used, the fossil fuel fraction of input energy can be reduced to 37% and 41% respectively. Production and use of both pellet types in co-firing have similar environmental impact generating CO₂-equivalent emissions from electricity in the range 43–45 g MJ⁻¹. An emission savings of 77% can be realised by co-firing torrefied pellets with fossil coal. Pellet production amounts correspond to 4.3 and 4.2 MJ generated electricity for each kilogram of feedstock (dry mass) and co-firing ratios (energy basis) in the range of 1.4–1.8%.

If only one mode of product transport is used torrefied pellet production and co-firing is found to generate fewer emissions than its conventional counterpart when transport distance is more than 400 km (lorry), 1850 km (rail) and 25,500 km (ship).

© 2014 Elsevier Ltd. All rights reserved.

* Corresponding author at: Department of Chemistry, University of Jyväskylä, P.O. Box 35, 40014 Jyväskylä, Finland.

E-mail address: david.a.agar@jyu.fi (D. Agar).

Nomenclature

A	annual logging residue harvest area (ha a^{-1})	P	annual production capacity at product moisture content (t a^{-1})
E	total CO_2 -equivalent emissions from the production of the fuel before energy conversion (g)	Q	annual thermal output of produced fuel (MJ)
EC_{el}	total CO_2 -equivalent emissions from the final energy commodity, that is electricity (g MJ^{-1})	q_{input}	total primary energy input from production of fuel (kJ t^{-1})
$EC_{F(el)}$	total CO_2 -equivalent emissions from the fossil fuel comparator for electricity, 198 (g MJ^{-1})	q_{output}	thermal energy output of produced fuel (kJ t^{-1})
e_{ec}	emissions from the extraction or cultivation of raw materials (g)	$q_{gr,prod,d}$	gross calorific value of product at constant volume on dry basis (MJ kg^{-1})
e_l	annualised emissions from carbon stock changes caused by land use change (g)	$q_{net,res,d}$	net calorific value of logging residue chips on dry basis (MJ kg^{-1})
e_p	emissions from processing (g)	$q_{net,prod,M}$	net calorific value of product at constant pressure at moisture content M (MJ kg^{-1})
e_{td}	emissions from transport and distribution (g)	RED	Renewable Energy Directive of the European Union
e_u	emissions from the fuel in use (g)	r_l	diesel consumption lorry ($\text{L t}^{-1} \text{km}^{-1}$)
e_{sca}	emission savings from soil carbon accumulation (g)	r_{rail}	diesel consumption shipping ($\text{L t}^{-1} \text{km}^{-1}$)
e_{ccs}	emission savings from carbon capture and geological storage (g)	r_{res}	diesel consumption, road-side chain (L ha^{-1})
e_{ccr}	emission savings from carbon capture and replacement (g)	r_{ship}	diesel consumption shipping ($\text{L t}^{-1} \text{km}^{-1}$)
f_{CH4}	methane formation from feedstock (kg t^{-1})	S_{el}	CO_2 -equivalent emission savings from electricity generated from solid biofuel
f_{loss}	dry matter loss (%)	V	annual volume of feedstock ($\text{m}^3 \text{a}^{-1}$)
G	useful energy gain (unitless)	$w(H)_d$	hydrogen content in dry fuel (%)
K	annual pulverisation energy use at product moisture content (kW h a^{-1})	$w(N)_d$	nitrogen content in dry fuel (%)
k	specific pulverisation energy at product moisture content (kW h t^{-1})	$w(O)_d$	oxygen content in dry fuel (%)
L_{FI}	maximum allowed lorry load in Finland (t)	W	annual net electricity generation (MJ a^{-1})
L_{ES}	maximum allowed lorry load in Spain (t)	X_{el}	upgrading electricity consumption (kW h a^{-1})
l_{feed}	lorry transport distance of feedstock (km)	X_{H2O}	upgrading water consumption ($\text{m}^3 \text{a}^{-1}$)
l_{prod}	lorry transport distance of product (km)	X_{ng}	upgrading natural gas consumption (kW h a^{-1})
l_{ship}	shipping distance of product (km)	X_{N2}	upgrading nitrogen consumption (kg a^{-1})
M_{feed}	moisture content of feedstock, logging residue chips (%)	Y	logging residues potential ($\text{m}^3 \text{ha}^{-1}$)
M_{prod}	moisture content of product (%)	Y_E	energy yield of torrefaction (%)
m_{feed}	annual feedstock use (t a^{-1})	Y_m	mass yield of torrefaction (%)
$m_{feed,d}$	annual feedstock use, dry basis (t a^{-1})	η_{el}	electrical efficiency, defined as the annual electricity produced divided by annual fuel input
$m_{torr,d}$	additional feedstock mass through torrefaction, dry basis (t a^{-1})	ρ_{feed}	bulk density of logging residue chips (kg m^{-3})
$N_{res,d}$	dry mass distribution of logging residues (t ha^{-1})	ρ_{prod}	bulk density of product (kg m^{-3})
		σ	energy density of product (GJ m^{-3})

1. Introduction

The use of solid (renewable) biomass fuels is a growing trend by which heat and power production can be made more sustainable. Fossil coal however continues to be a widely used fuel in the energy sector because of economics, existing power plant design and infrastructure. Direct co-firing of biomass with coal has potential in significantly reducing net carbon dioxide emissions. Direct co-firing assumes the fuel is mixed with coal upstream of coal feeders. The fuel mix is pulverised in existing coal mills and forwarded to the burners. This is recognised as the simplest method of co-firing and also is seen as the cheapest option in terms of capital investment [1]. With untreated biomass co-firing is practically limited to 5–10% (energy basis) due to unfavourable properties of biomass; poor energy density, high moisture content and fibrous nature [1].

Wood pellets made from by-products of the wood processing industry have been used in co-firing. Their production in Europe is a well-established industry with inland production at some 12 million tonnes in 2010. Large amounts of wood pellets are already imported from North America to meet growing European demand. Based on recent estimates a 5% replacement of coal (energy basis) with wood pellets at European coal plants would require an equivalent annual production of 33 million tonnes [2].

1.1. Torrefaction

Recently, there has been great interest in *torrefaction* which is a roasting process carried out in the absence of oxygen. After torrefaction woody and agro biomass have properties a step closer to fossil coal. Improved properties include a higher calorific value, lower equilibrium moisture content [3] and improved friability. Additionally, pellets made of torrefied biomass – herein referred to as *torrefied pellets* – have a greater volumetric energy density than those of untreated feedstock. The process and expected environmental benefits of torrefied biomass have been described elsewhere [4] and available experimental data on some key properties for co-firing applications have been compiled [5].

If torrefaction technology is widely adopted it will bring changes in the way biomass resources are utilised. For example, high-quality wood feedstock may find better use in torrefied pellet production than conventional. Consequently greater amount of pellets and therefore biomass could end up at coal power plants due to the enabling of higher co-firing rates.

Several different torrefaction reactor technologies are under development at pilot-scale plants throughout Europe and America but at present there is a lack of semi-industrial production data about torrefied pellets. Without production data on consumable inputs and heat and mass balances, the environmental impact of

the technology can only be estimated based on the properties of torrefied materials found in laboratory studies [5] which in no way reflect the technical feasibility of reactors.

1.2. Feedstock supply in Europe

Even a conservative estimate of blending 20% torrefied biomass with coal in European plants would translate to an annual production of over 100 million tonnes. Inland feedstock demand would necessarily lead to greater utilisation of other biomass resources.

Understandably torrefaction has raised concerns that biomass resources outside of Europe may be utilised in order to realise emission reductions within the Union. For example, torrefied pellet production could take place in South America or Africa where feedstock is cheaper, more plentiful and wages lower. However, this would not comply with the other objective of EU energy policy; to secure inland sources of energy.

1.3. Logging residues

Extractable logging residues (tree tops and branches) exist in large volumes in Finland having an estimated annual volume (2000) of at least 10 million cubic metres [6] – or about four million tonnes per year. This figure is based on the assumption that residues amount to 15% of stem wood mass for coniferous trees and 10% for deciduous [6]. Logging residues are already widely harvested and used in Nordic countries at grate-fired and fluidised-bed power plants both of which are designed for heterogeneous wet solid fuels but this feedstock has also been shown to be a suitable raw material for pellet production [7]. Additionally, studies suggest that the utilisation of residues from Nordic forests is more environmentally beneficial than leaving them on the forest floor and can lead to maximum benefit when offsetting fossil coal use at power plants [8,9].

1.4. Environmental impact assessment

The aim of this environmental impact assessment is to estimate two quantities: the use of energy input for an operation known as *primary energy* use and the amount of generated CO₂-equivalent air emissions. The Renewable Energy Directive (RED) provides sustainability criteria by which alternate production methods can be compared based on their CO₂-equivalent air emissions to the environment [10]. The use of these criteria for determination of emissions from two different products from the same raw material negates the need of analysing the entire life-cycle of both products. Rather it simplifies the comparison by focusing on relative differences between two products. This is sensible for well-established industries such as the wood pellet industry. In any case direct comparison of results in literature is not always possible due to differences in chosen system boundaries. As a newly emerging technology torrefied pellet production has not been treated with RED criteria based on real production data.

1.5. Environmental impact of wood pellets and logging residue chips

Environmental impact assessment has previously been carried out on conventional wood pellets [11]. Magelli et al. find that primary energy input for Canadian wood pellets produced in British Columbia and delivered to Sweden is 7.2 GJ per tonne and that CO₂-equivalent emissions from their production and transport is 29 g MJ⁻¹. These figures assume feedstock material is used as a fuel in the drying process. Over one third of input energy from Canadian pellets stems from transatlantic shipping via the Panama Canal to Stockholm and in total 39% of the energy content of these pellets is consumed in their manufacture and transport [11]. If the

same pellets were used domestically the energy input could be reduced to 4.6 GJ per tonne. Based on RED criteria and these values the use of the pellets for strictly heating in Sweden would realise an emissions saving of about 60% compared to coal (assuming a boiler efficiency of 80%).

For comparison Nordic production (Sweden) of logging residue chips is found to have an energy input range of only 0.4–0.5 GJ per tonne [12]. Additionally chip production from loose (non-bundled) residue collection required the lowest primary energy input (21–27 kJ MJ⁻¹) of several studied production scenarios and generated the least amount of CO₂-equivalent air emissions (1.5–1.9 g MJ⁻¹). The above values assume that the fuel's full net calorific value (LHV) can be realised in combustion [12]. This is often not the case since residue chips have greater moisture content because they are not typically dried like the feedstock used to make wood pellets.

When considering the difference between wood pellets and logging residue chip production it is noted that the pellet production study takes into account emissions and energy input from the final felling of timber from which pellet feedstock is derived (including the hauling of stem wood a distance of 110 km) whereas the above residue chip production does not include this operation [12].

1.6. Impact of torrefied pellet production from logging residues

The impact of using biomass in different co-firing pathways in Alberta, Canada, has been studied. Two pathways of interest here are those of conventional and torrefied pellets produced from logging residues. In their work, Kabir and Kumar considered in-province harvest, production and end use of these two pellet types and evaluated impacts from the entire life cycle of the pathway. They found that the total CO₂-equivalent air emissions from direct co-firing in electricity production were 68 and 47 g MJ⁻¹ for conventional and torrefied pellets respectively [13]. They also calculate a net energy ratio (NER) of 1.6 and 1.1 for these two fuels – indicating that the power generated over the lifetime of the pathway is greater than the non-renewable primary energy input of the fuel. Despite a modest product transport distance (500 km) their results indicate that torrefaction as an upgrading process has a clear beneficial impact. Although the Kabir and Kumar study is a recent one (2011) their results depend on torrefied pellet properties and production technologies which they acquired from an early proprietary report on torrefaction [14]. More recent peer-reviewed studies on torrefied pellet properties however have indicated that ideal torrefied pellet properties are somewhat compromised due to the limitations imposed by semi-industrial production. For example, certain key properties such as the increase in calorific value, equilibrium moisture content, ability to pelletise and volumetric energy density have been shown to be less favourable in produced torrefied pellets [3,15]. Environmental performance of a fuel is strongly dependent on these properties.

1.7. Purpose and scope of study

In this study data on consumable inputs from a semi-industrial torrefaction plant and the physical properties of produced pellets are used to analyse energy input and air emissions of torrefied pellet production and product transport. EU sustainability criteria are used to compare CO₂-equivalent emissions from torrefied and conventional pellet production starting from the harvest of logging residues to end use in combustion. Pellet production utilises Nordic logging residues as feedstock. In this scenario, pellets are produced in the far north of the EU and transported to the south where they are co-fired with coal for the production of electricity.

The production scenario considered herein is of interest because it conforms to EU energy policy objectives by keeping production of biofuels within the Union and by realising reductions in net

carbon dioxide emissions from the energy sector. Moreover, the transport distance used in this intra-European scenario is close to the maximum within the present day EU.

By comparing the environmental impact of production of these two pellet types the following research questions can be answered: What is the environmental impact of torrefied pellet production and use compared to that of conventional wood pellet production? What magnitude of net emission savings can be expected from off-setting fossil coal use with these fuels? Does the higher energy density of torrefied pellets result in significant energy and emission savings via transport? How does product transport distance by lorry, rail and ship affect total emissions in quantitative terms? The economics of producing torrefied pellets will depend on a number of technical and economic factors that are not addressed in the present study but the consumable inputs of scaled-up production are presented.

2. Methodology

The Spanish National Renewable Energy Centre (CENER) operates a Second Generation Biofuels centre (CB2G) which includes a pilot-scale torrefaction facility. The facility, located in Aoiz, has the capacity to process up to 500 kg h⁻¹ of biomass feedstock [16]. CENER's proposed torrefaction concept is shown in Fig. 1.

The torrefaction process concept is heat integrated. The combustible vapours generated in the torrefaction reactor are treated in a thermal oxidiser taking advantage of energy in an attached boiler to heat up the thermal fluid. To optimise reactor throughput, it is convenient to dry the biomass before torrefaction. Flue gases from the boiler at temperatures higher than 300 °C are fed to the drier. Additional fuel could be necessary for drying, depending on biomass moisture content and target torrefaction degree.

The core of the process equipment is the torrefaction reactor. It is a cylindrical horizontal reactor with an agitator shaft and attached elements of special design procuring axial transport characteristic for all kind of biomass, radial product homogenisation inside the reactor and excellent heat transfer conditions. The reactor is capable of transporting biomass with low bulk density values (from 50 kg m⁻³ and upwards) and high amounts of fines and dust material, up to 89% in amount of fines (≤3.15 mm) and up to 62% in dust content (<250 μm) has been tested successfully. Reactor heating is carried out indirectly through the hot reactor walls, the actively heated shaft tube and the actively heated internal shaft elements using thermal oil as heat transfer fluid.

The torrefaction reactor scale-up to industrial size is based on a reactor model developed at CENER. The main features of the model include:

- Perfectly-mixed reactors are modelled in series. Product output from one stage forms input of the next stage.
- Torrefaction process is according to the kinetic model of Di Blasi and Lanzetta [17].
- Kinetic parameters are obtained by thermogravimetric analysis of studied feedstock.
- Feedstock intra-particle temperature profiles are neglected (i.e. particles are isothermal).
- Heat of reaction is a function of reaction temperature (correlations developed from pilot test energy balance).
- Gas–solid heat transfer is neglected.
- Mass and energy balance equations are solved for each stage.
- The model calculates: conversion, temperature profile, gas temperature and heat demand of the reactor.
- Reactor heat losses are measured at pilot scale and extrapolated to industrial scale based on correlation of the reactor manufacturer.

A general mass and energy balance spreadsheet has been developed for process integration of drying, torrefaction and valorisation of torrefaction gases. Modelling has been verified by pilot testing at 200–400 kg h⁻¹ production rate. Data on torrefied pellet properties and amount of consumable inputs have been obtained from production data from the CENER CB2G pilot facility.

Fig. 2 describes the thermal balance of scaled-up industrial production (40,000 tonnes annually) of a torrefaction plant based on the CENER concept and pilot-scale data. Thermal input and output values are shown in Fig. 2 for annual plant operation of approximately 7724 h. The thermal efficiency of the process is equal to the thermal output of the torrefied feedstock (28,485 kW) divided by the sum of thermal inputs (33,224 kW). The thermal efficiency of the process is 86%. Among other influencing factors, the thermal efficiency of torrefaction depends directly on the net calorific value of the product and inversely on the moisture content of feedstock. Thermal losses stem from flue gas, product cooling, radiative heat loss and ash amount to 14%.

The mass and energy yields of torrefaction are defined as follows:

Mass yield of torrefaction (dry basis)

$$Y_m = \left(\frac{\text{mass of product}}{\text{mass of feedstock}} \right)_{\text{dry basis}}$$

Energy yield of torrefaction (dry basis)

$$Y_E = Y_m \left(\frac{\text{GCV of product}}{\text{GCV of feedstock}} \right)_{\text{dry basis}}$$

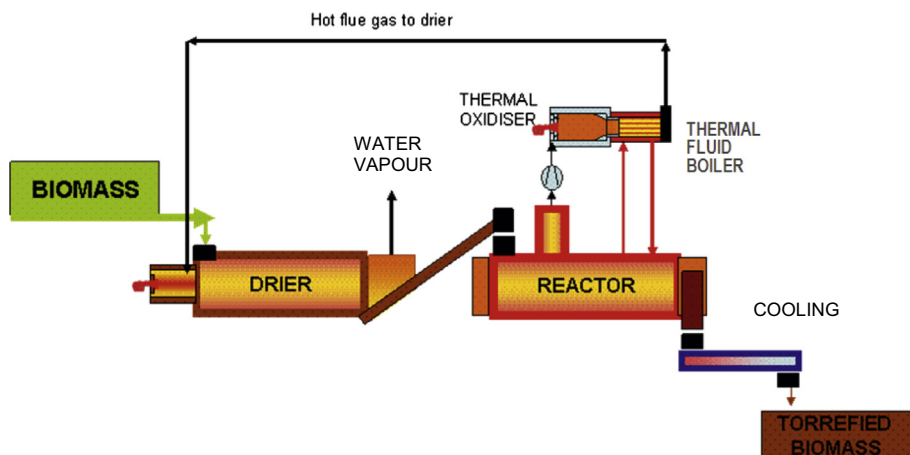


Fig. 1. Schematic diagram of the torrefaction process concept under development at the Spanish National Renewable Energy Centre (CENER).

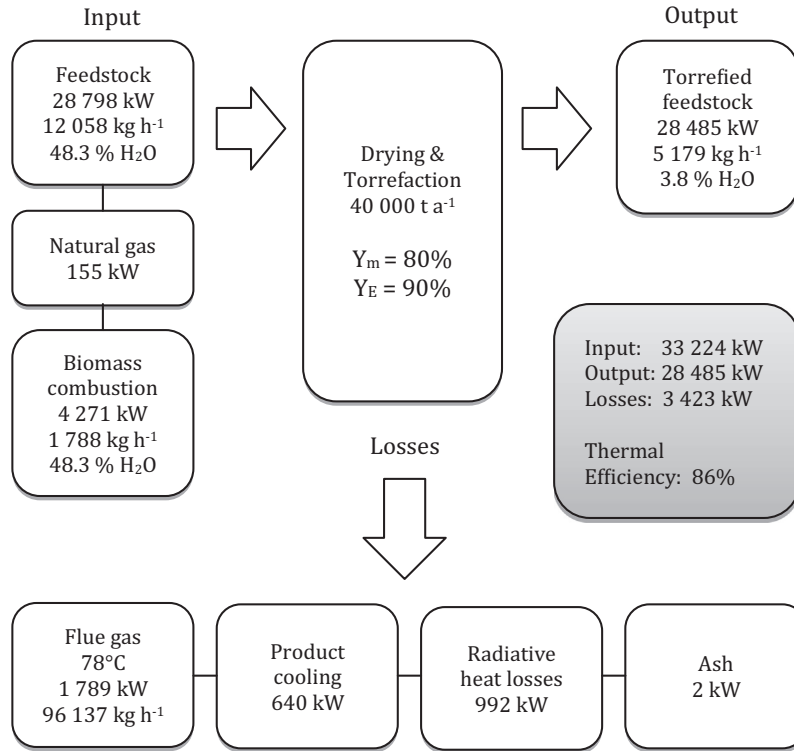


Fig. 2. The thermal balance of scaled-up industrial torrefaction plant for annual production of 40,000 tonnes torrefied biomass. Based on inputs and outputs the thermal efficiency of the process is 86%. Thermal losses stem from flue gases, product cooling, radiative loss and ash.

Using these relations the mass and energy yields (dry basis) for the system shown in Fig. 2 are 80% and 90% respectively.

Other inputs to the torrefaction process (not shown in Fig. 2) include nitrogen gas, used in purging conveying lines to minimise ignition risks, air for drying and electricity used in process control, conveying feedstock and pelletisation.

2.1. Energy and CO₂-equivalent emission balance methodology

The Renewable Energy Directive 28/2009/EC (RED) contains a sustainability scheme which covers biofuels used in transport and bio-liquids used in other sectors such as electricity, heating and cooling [10]. Since the time of its publishing the EU Commission has produced a report on a subsequent sustainability scheme for the use of solid and gaseous biomass in electricity, heating and cooling. A future directive on sustainability within this topic is expected to be of this form and methodology. Therefore, this methodology was chosen for use in the calculations of CO₂-equivalent emission balance herein. Annex I of the report (which parallels Annex V of RED) contains the following three equations for the calculation of emissions from the production of solid biomass fuels [18].

Eq. (1) is used to calculate the total emissions E from the production of the solid biomass fuel before energy conversion. This is simply the sum of the emissions from harvesting (e_{ec}), land-use changes (e_l), processing (e_p), transport (e_{td}) and utilisation (e_u) with emission savings from any soil carbon accumulation (e_{sca}) or carbon capture (e_{ccs} and e_{ccr}) subtracted.

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \quad (1)$$

The total emissions from the final energy commodity EC_{el} (in this case electricity) are found by dividing Eq. (1) by the efficiency of electrical generation η_{el} at the plant where the fuel is combusted.

$$EC_{el} = \frac{E}{\eta_{el}} \quad (2)$$

The use of the biofuel results in an emission savings S_{el} when compared to the use of fossil fuel. The extent of this savings is found by using Eq. (3) in which the fossil fuel comparator $EC_{F(el)}$ is used.

$$S_{el} = \frac{EC_{F(el)} - EC_{el}}{EC_{F(el)}} \quad (3)$$

When comparing the production of two or more fuels, the concept of *useful energy gain* G is helpful. This value, found using Eq. (4), is the ratio of the thermal energy output q_{output} extracted from the produced fuel to q_{input} the energy used in its production. This relation is a function of $q_{net,prod,M}$ net calorific value of the fuel.

$$G = \frac{q_{output}}{q_{input}} = \frac{q_{net,prod,M}}{q_{input}} \quad (4)$$

2.2. The production scenario

The scenario used for this study compares the energy and CO₂-equivalent emission balance from the production of conventional pellets to that of torrefied pellets. Both pellet types are produced from the same feedstock; logging residues from final timber harvest. The system considered starts from the logging residue harvesting operation and ends with the direct co-firing of pellets with fossil coal – the final felling operation is outside the system boundary. Table 1 outlines the stages of the scenario including geographical location considered.

Case 1 considers that both fuels are produced in the vicinity of Riistina, Finland. This site was chosen because plans for a commercial plant in the same area were announced in the Finnish media in February 2012 with a completion date in 2015 [19]. The fuels are

Table 1

Production and transportation overview of two conventional and torrefied pellet production cases considered in this study.

Case	Supply	Production site	Lorry (km)	Rail (km)	Ship (km)	Shipping port	Receiving port	End use
1	Final harvest logging residues	Riistina, Finland	178	0	3361	Kotka	Coruña, Spain	Co-firing at Meirama Central
2		Prince George, Canada	0	781	15,500	Vancouver		

then transported by lorry, shipped to the western Spanish port of *Coruña* (from the Finnish port of *Kotka*). Co-firing of the fuels takes place at the *Meirama Central* coal power plant which has a maximum electrical power output of 563 MW but an average annual (1998–2007) electrical production of 12,433 TJ [24]. Case 2 includes the same production as in Case 1 but a production site in western Canada which is representative of a long-distance transport distance for pellets being the same as those used in another relevant study [11].

The production scenario is divided into four stages: *Supply*, *Upgrading*, *Transport* and *End Use*. These are labelled and depicted in Fig. 3 as the larger cells, within which separate operations are described. The first two stages take place in Finland and the last stage takes place in Spain. The second stage is based on road-side storage and chipping of seasoned final harvest logging residues. In terms of modelling this scenario, it is only in the Upgrading stage that operations for the two types of fuel production differ; torrefaction is absent from conventional pellet production. Transport of feedstock is included in the Supply stage so that product transport emissions and energy can be evaluated separately.

To determine energy and emission balance of each stage, operations are described in terms of their consumable inputs and resulting outputs which are firstly identified. For example, the collection of logging residues from a timber harvest area requires an input of diesel fuel for the forwarders. By knowing the amount of diesel used, the energy input and generated emissions from this operation can be found by use of an energy and emission factor which is specific for diesel. Outputs are by-products of an operation which may contribute to emission balance. An example of an output is methane emissions produced as a result of non-intentional anaerobic decomposition of piled logging residues at the roadside.

Table 2 contains the energy and CO₂-equivalent emission factors used in the calculations. The total energy and emission balance for each of the four stages in Fig. 2 can be found by summing up all the contributing values from each operation.

Table 2

Energy and CO₂-equivalent emission factors of production scenarios inputs and outputs. Energy and emission factors are taken from Official Journal of the European Union except for water and nitrogen values which are from Ecoinvent Database. N.A. indicates Not Applicable.

Input/output (unit)	Energy factor		CO ₂ -equivalent emission factor	
	Symbol	Value (kJ)	Symbol	Value (g)
Diesel (L)	D_{diesel}	41,597	C_{diesel}	3143
Electricity (kW h)	D_{el}	9819	C_{el}	465
Natural gas (kW h)	D_{ng}	4061	C_{ng}	243
Utility water (m ³)	D_{H2O}	5337	C_{H2O}	263
Nitrogen gas (kg)	D_{N2}	9189	C_{N2}	436
Methane (kg)	N.A.	N.A.	C_{CH4}	25,000

2.3. Calculations

The input variables used for the calculation of mass and energy balances of the four production stages for the two compared fuels are given in Table 3. Some input values are also given with a range which reflects the variance of data found in cited literature.

The set of relations used to calculate physical quantities are given below. These quantities are either necessary for determination of energy and emission balance or are of interest when comparing the production of two fuels. The dry mass distribution of logging residues $N_{res,d}$ depends on residue potential Y and bulk density ρ_{res} chipped material with M_{res} moisture content.

$$N_{res,d} = Y\rho_{res} \left[\frac{1 - (M_{res}/100)}{1000} \right] \quad (5)$$

In conventional pellet production the dry mass of feedstock is conserved in the final product.

In order to produce the same tonnage of torrefied pellets at moisture content M_{prod} however additional feedstock $m_{torr,d}$ is required because of mass loss during torrefaction (Fig. 2). The

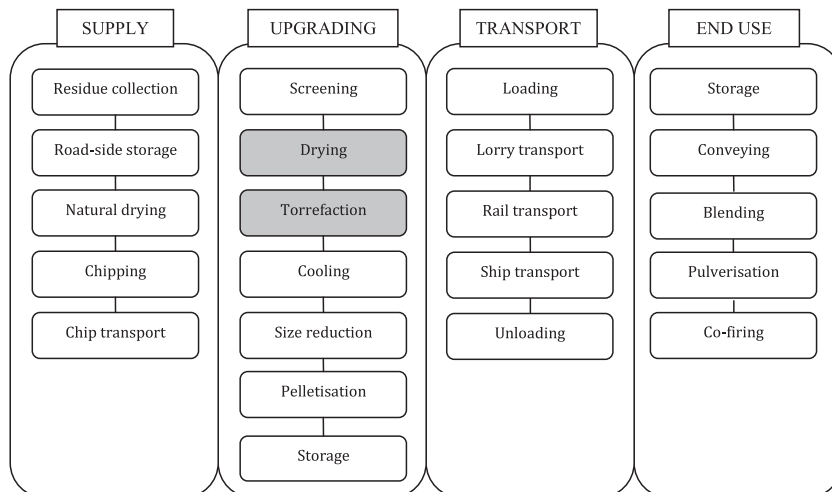


Fig. 3. The four stages of the pellet production and supply chain are represented by the larger cells. Separate stage operations are depicted in the order they occur. Drying and torrefaction operations are described in Fig. 2. The final felling operation of forest at the site from which logging residues are collected is outside the system boundary.

Table 3

Input values (and range) used in determining emission and energy balance of production cases of conventional and torrefied pellets. Symbols in the table refer to (a) based on scaled-up production data from CENER pilot-plant (b) calculated value (c) country-specific lorry load restriction and (d) estimated value (e) determined using Google Maps (www.google.com).

Symbol	Units	Conventional pellets			Torrefied pellets		
		Value	Range	Ref.	Value	Range	Ref.
Y	$\text{m}^3 \text{ha}^{-1}$	100	70–130	[20]	100	70–130	[20]
ρ_{res}	kg m^{-3}	325	250–400	[21]	325	250–400	[21]
M_{res}	%	55	50–60	[21]	55	50–60	[21]
$q_{\text{net,res,d}}$	MJ kg^{-1}	18.5	18.5–20.0	[21]	18.5	18.5–20.0	[21]
r_{res}	L ha^{-1}	152	106–198	[21,22]	152	106–198	[21,22]
f_{CH_4}	kg t^{-1}	0.01		d [23]	0.01		d [23]
f_{loss}	%	1.6		[12]	1.6		[12]
$m_{\text{feed,d}}$	t a^{-1}	42,150		b	55,288		a
P	t a^{-1}	40,000		a	40,000		a
M_{feed}	%	48.3		d [20]	48.3		d [20]
$q_{\text{gr,prod,d}}$	MJ kg^{-1}	17.5	16.9–18.0	d [21]	20.7		a
$w(\text{H})_d$	%	6.1		[24]	6.00		a
$w(\text{O})_d$	%	41		[24]	39.5		a
$w(\text{N})_d$	%	0.5		[24]	0.18		a
V_{feed}	$\text{m}^3 \text{a}^{-1}$	250,854		b	329,045		b
A	ha	2882		b	3780		b
ρ_{prod}	kg m^{-3}	625	560–690	[21]	680		a
x_{el}	kW h a^{-1}	5.88×10^6		[25]	8.64×10^6		a
x_{ng}	kW h a^{-1}	0			1.20×10^6		a
x_{N_2}	kg a^{-1}	0			2.55×10^6		a
$x_{\text{H}_2\text{O}}$	$\text{m}^3 \text{a}^{-1}$	0			5000		a
L_{FI}	t	60		c	60		c
L_{ES}	t	40		c	40		c
r_l	$\text{L t}^{-1} \text{km}^{-1}$	0.0760	0.0433–0.108	[26]	0.0760	0.0433–0.108	[26]
l_{feed}	km	25		d	25		d
l_{prod}	km	178		e	178		e
r_{rail}	$\text{L t}^{-1} \text{km}^{-1}$	0.01683		[27]	0.01683		[27]
r_{ship}	$\text{L t}^{-1} \text{km}^{-1}$	1.20×10^{-3}		[27]	1.20×10^{-3}		[27]
l_{ship}	km	3361		[28]	3361		[28]
η_{el}	%	29.1		[29]	29.1		[29]
M_{prod}	%	10	7–12	[21]	3.8	2.2–8.7	a [5]
$q_{\text{net,prod,M}}$	MJ kg^{-1}	15.5		b	19.8		b
σ	GJ m^{-3}	10.1		b	13.5		b
V_{prod}	$\text{m}^3 \text{a}^{-1}$	61,538		b	58,824		b
k	kW h t^{-1}	50	241–840	d [30,31]	15	52–150	d [30,31]

annual feedstock use on dry basis for annual production amount P of torrefied pellets is then

$$m_{\text{feed,d}} = P \left[1 - \left(\frac{M_{\text{prod}}}{100} \right) \right] + m_{\text{torr,d}} \quad (6)$$

The required harvest area A of land to supply the total annual production of pellets is then

$$A = \frac{m_{\text{feed,d}}}{N_{\text{res,d}}} \quad (7)$$

The total feedstock volume can be found from (wet) annual feedstock use m_{feed} and bulk density of logging residue chips ρ_{feed} .

$$V = \frac{m_{\text{feed}}}{\rho_{\text{feed}}} \quad (8)$$

The net calorific value of produced pellets (Eq. (9)) is found as a function of moisture content M in addition to the content of hydrogen $w(\text{H})_d$, oxygen $w(\text{O})_d$ and nitrogen $w(\text{N})_d$ in the dry fuel. This relation is found in annex C of the European standard for determination of calorific value [24].

$$q_{\text{net,prod,M}} = \{q_{\text{gr,prod,d}} - 212.2 \times w(\text{H})_d - 0.8 \times [w(\text{O})_d + w(\text{N})_d]\} \times (1 - 0.01M) - 24.43 M \quad (9)$$

The annual thermal output Q of fuel is equal to the product of annual production amount P and the net calorific value.

$$Q = P q_{\text{net,prod,M}} \quad (10)$$

The energy density (Eq. (11)) represents how much energy is contained within a cubic metre of space. Calculated σ values only have meaning when bulk density ρ value corresponds to the same level of moisture and hence specific net calorific value (Eq. (9)).

$$\sigma = \rho \cdot q_{\text{net,prod,M}} \quad (11)$$

The annual energy use K for grinding the fuel to a powder with coal depends on the fuel's specific pulverisation energy requirements k which in practice is influenced by moisture content, scale of mill and its design. This is electrical energy used at the power plant.

$$K = k \cdot P \quad (12)$$

Finally, the annual net electricity generated at the power plant through combustion of produced fuel is the product of the annual thermal output of fuel and the efficiency of electrical generation.

$$W = Q \cdot \eta_{\text{el}} \quad (13)$$

2.4. Assumptions

The main assumptions made in the production scenario are summarised below.

- Logging residues are suitable for production of quality pellets [7].
- The final felling operation at the site from which logging residues are collected is outside the system boundary depicted in Fig. 3.
- Annual dry mass loss from feedstock is estimated to be 1.6%.

- Some methane formation from feedstock is assumed [23].
- No additives are used in pelletisation of both pellet types.
- Limited natural drying of forest residues takes place and the average moisture content of feedstock is the same as that delivered to large power plants in Finland [20,21].
- The average supply distance from harvest to pellet production site is 25 km.
- Lorries used for feedstock delivery travel empty one way.
- There are no empty lorry loads in pellet transport.
- Wet feedstock is combusted and used for drying before torrefaction (Fig. 2).
- For both pellet types electricity is used for size reduction and pelletisation.
- Loading and unloading operations of products are not taken into account.
- There are no carbon stock changes from land where residues are harvested ($e_l = 0$).
- Associated emissions from other co-firing operations at power plant not taken into account ($e_u = 0$).
- The cut-to-length Nordic logging method is not utilised in Canada but Case 2 assumes that similar residue amounts would be available.
- The efficiency of electrical generation at power plant is not fuel dependent.
- Electricity used for pulverising fuels at power plant comes from the external electrical grid.
- The energy required for pulverisation is estimated as 50 and 15 kW h t⁻¹ for wood and torrefied pellets respectively.

The last stated assumption above requires justification. At present industrial-scale energy requirements for pulverising wood and torrefied pellets is not well documented. Energy requirements depend on the target particle size for effective combustion. Successful combustion in pulverised-fuel systems requires fuel with a large surface-to-volume ratio but also a minimum amount of larger particles to achieve high combustion efficiency [32].

Differences in fuel volatility mean that optimal particle size for torrefied biomass is not the same for coals. Suitable particle size for most coal types which includes high-grade ones is 70% of particles passing through a sieve opening of about 75 μm with all other particles passing through a 300 μm sieve opening [32]. The equivalent particle size for torrefied biomass enabling effective combustion will be larger than that of coal. Recent co-firing trials with Bulga coal in 0.5 MW boilers indicate that combustion efficiency remains constant or increases slightly with a co-firing rate of 30% to 70% torrefied pellets [33]. Furthermore the measured particle mass fraction distribution from these trials showed a gradation to a larger fraction of larger particle as coal fraction decreased in the fuel blends.

Energy consumption (electrical) for coal pulverisation has a reported range of 7–36 kW h t⁻¹ [34] while the range for (non-torrefied) biomass begins at 40 kW h t⁻¹ [1]. Based on laboratory-scale milling experiments carried out on both untreated and torrefied wood and logging residues, grinding of the torrefied materials requires 11–32% of the energy needed compared to untreated material [5]. At industrial scales the relative differences in required energy are likely to remain. Therefore an estimate of 50 and 15 kW h t⁻¹ for the pulverisation energy requirement of wood and torrefied pellets respectively has been used. Based on recent work [35] the former value for wood pellets appears justified at particle sizes below 2 mm.

With the assumptions made in this production scenario, the total emissions from the production of the solid biomass fuels before energy conversion (Eq. (1)) can be simplified as $E = e_{ec} + e_p + e_{td}$. This has been calculated using the factors given in Table 2 and the following relations:

Emission from harvesting

$$e_{ec} = (r_{res} \cdot A)C_{diesel} + (f_{CH_4} \cdot m_{feed,d})C_{CH_4} \quad (14)$$

Emissions from processing

$$e_p = (x_{el} + k \cdot P)C_{el} + (x_{ng} \cdot C_{ng}) + (x_{N_2} \cdot C_{N_2}) + (x_{H_2O} \cdot C_{H_2O}) \quad (15)$$

Emissions from transportation

$$e_{ec} = [r_l(m_{feed} \cdot l_{feed} + P \cdot l_{prod})]C_{diesel} \quad (16)$$

3. Results and discussion

3.1. CO₂-equivalent emissions

The total CO₂-equivalent emissions per unit of produced electricity (Eq. (2)) for Case 1 and 2 are presented in Fig. 4 showing the contributions from each stage. The fossil fuel comparator value for electricity from coal is 198 g MJ⁻¹ [10]. Production and use of both pellet types have a similar environmental impact generating CO₂-equivalent emissions in the range 43–45 g MJ⁻¹. This range agrees well with the value found by Kabir and Kumar (47 g MJ⁻¹) for torrefied pellets made from logging residues [13] despite the fact that lifecycle emissions from the production plant themselves have not been considered herein.

The emission savings (Eq. (3)) from the use of pellets in co-firing are approximately 78% for conventional pellets and 77% for torrefied pellets for production in Finland while savings are 74% for both pellet types in the case of production in Canada. The total annual emissions of CO₂-equivalent for Case 1 (Eq. (1)) are 7746 t and 10,366 t for conventional and torrefied production. The emissions per tonne of product from each production stage (Fig. 3) are: 46.8, 68.4, 55.2, 23.3 kg t⁻¹ (conventional pellets) and 61.4, 136, 55.2, 6.98 kg t⁻¹ (torrefied pellets).

CO₂-equivalent emissions from torrefied pellet production exceed those of conventional pellet production in both of the cases considered. Torrefied pellets have greater Supply and Upgrading stage emissions but lower Transport and End Use emissions.

3.2. Uncertainty in logging residue potential

Error bars have not been used in Fig. 4 but it is noted that the range of values given in Table 3 variables for inputs of logging residues potential (Y), bulk density of residue chips (ρ_{res}) and moisture content of chips (M_{feed}) contribute to the Supply stage

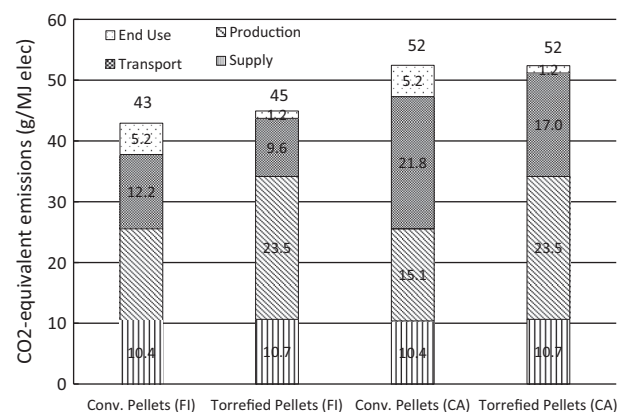


Fig. 4. The total emissions from the final energy commodity (Eq. (2)) from the considered production and supply scenario of conventional and torrefied pellets in case of production in Finland (FI) and Canada (CA). The fossil fuel comparator value for electricity from coal is 198 g MJ⁻¹.

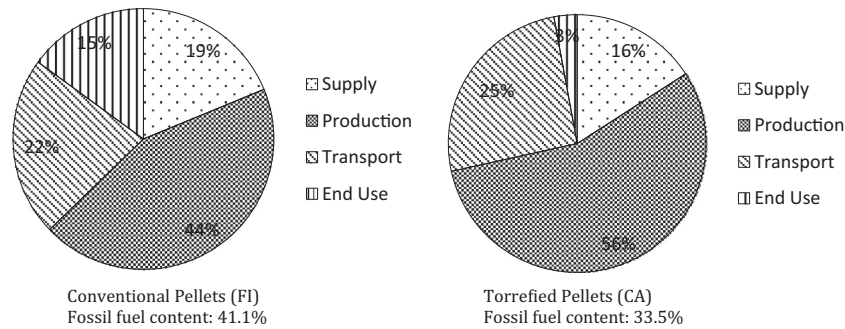


Fig. 5. Division of primary energy use per tonne product in pellet production and use from conventional pellets in Finland (FI) and torrefied pellets in Canada (CA) used in co-firing in Spain. Total primary energy inputs are 3.3 GJ t^{-1} (conventional) and 5.1 GJ t^{-1} (torrefied).

emissions and thereby affect the total emissions by $\pm 4 \text{ g MJ}^{-1}$ or roughly $\pm 2\%$ of the emission savings.

3.3. Primary energy use

Based on the calculated primary energy input for Case 1 approximately 3.3 GJ of energy is consumed for each tonne of conventional pellets produced and co-fired. The corresponding value for torrefied pellets is 4.5 GJ . This contributes to a useful energy gain G (Eq. (4)) of 4.7 for conventional pellets and 4.4 for torrefied pellets; or inversely 21% and 23% of the energy content of the pellets respectively goes into producing and utilising them. The greater G value of the former indicates that it gives a better payback of energy investment – generating more energy output for a given energy input. The primary energy input of conventional pellet production in Finland (Case 1) and torrefied pellet production in Canada (Case 2) can also be compared (see Fig. 5).

3.4. Harvest area, net electricity generation and co-firing ratio

After taking into account dry mass losses, annual feedstock use (dry basis) for production is $42,150 \text{ t}$ for conventional pellets compared to $55,288 \text{ t}$ for torrefied; 31% greater amount for the torrefied product. This amount of feedstock corresponds to an annual harvest area A (Eq. (7)) of 2882 and 3780 ha for the two product types.

The calculated annual net electricity generation (Eq. (13)) from combustion of the two fuels is 180 and 230 TJ for conventional and torrefied pellets. Considering annual feedstock use above this equates to roughly 4.3 and 4.2 MJ generated electricity for each kilogram of feedstock (dry mass) for conventional and for torrefied pellets respectively.

Based on Meirama power plant's average electrical production the co-firing of produced pellets corresponds to co-firing ratios (energy basis) of 1.45% for conventional pellets and 1.85% for torrefied pellets. These values are well below feasible direct co-firing limits for plants designed to burn pulverised coal without additional infrastructure investments [1,32].

3.5. Fossil fuel content of pellets

If the electricity used in the pellet production stage and in pulverisation at the power plant would come from strictly renewable sources then for each tonne of produced pellets the fossil-fuel content (diesel and natural gas) of energy input could be reduced to 41% and 37% for conventional and torrefied pellets respectively – fossil fuel input represents 8.7% and 8.4% of the energy content of the pellets.

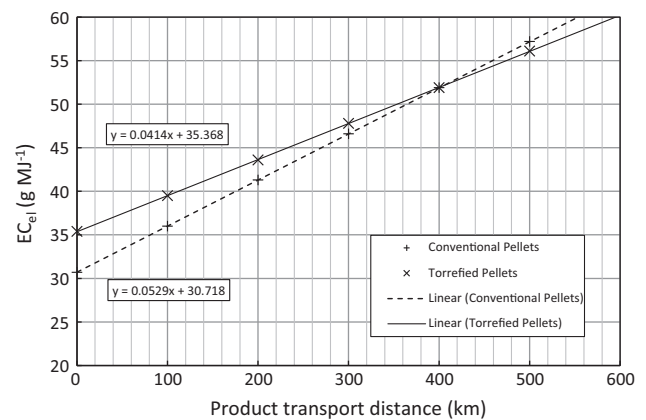


Fig. 6. Total generated CO_2 -equivalent emissions from final energy commodity (EC_{el}) from conventional and torrefied pellet production as a function of lorry transport distance of product. Assuming only lorry transport, total emissions for torrefied pellet production and use are less at transport distances greater than 401 km .

3.6. Minimum transport distance

Through torrefaction the calorific value of the feedstock is improved which leads to a greater volumetric energy density of pellets. Considering only one mode of transport, how large does the product transport distance need to be in order for total generated CO_2 -equivalent emissions of torrefied pellets to be lower than that of conventional pellets? This depends on the type of transport. Fig. 6 shows equations for the total emissions EC_{el} of the two pellet types as a function of lorry transport distance of product (assuming no other modes of transport). The vertical axis intercept represents sum of emissions from Supply, Upgrading and End Use stage. The intersection of the two lines (401 km) represents the point of equal emissions. At a distance greater than this, the total emissions of torrefied pellet production and use are less than that of conventional pellets. Similar equations can be found for the two other modes for which the points of intersection occur at 1844 km (rail) and $25,650 \text{ km}$ (ship).

4. Conclusions

Torrefaction is an emerging technology which enables greater co-firing rates of biomass with coal. Data on consumable inputs from a semi-industrial torrefaction plant and the physical properties of produced pellets have been used to analyse energy input and air emissions of torrefied pellet production and end use in co-firing.

Using sustainability criteria of the Renewable Energy Directive, emissions from the final energy commodity (electricity) are 45 g MJ⁻¹ for torrefied pellets and 43 g MJ⁻¹ conventional pellets. Co-firing with either of these fuels would result in emission savings of 77% and 78% respectively compared to the emissions from fossil coal.

Torrefied pellet production generates similar CO₂-equivalent emissions as conventional pellets for the studied intra-European production scenario. Due to the improved fuel properties of torrefied pellets however use of this fuel would enable higher rates of direct co-firing and hence greater volumes of biomass to be combusted. Consequently, greater biomass utilisation would enable further large CO₂-equivalent emission reductions from the energy sector. Results from research on industrial-scale size reduction (pulverisation) and combustion using torrefied pellets is desirable in future in order to better evaluate the environmental impact of co-firing with this fuel.

Acknowledgements

The study presented in this paper is the result of collaboration between the University of Jyväskylä (JYU) and the Spanish National Renewable Energy Centre (CENER). First contact between Finnish and Spanish authors was made possible through the BIOCLUS Project funded by the EU Seventh Framework Programme (FP7). A two-month collaboration between author organisations was funded in part by the JYU International Research Mobility Grant. The Finnish authors wish to thank personnel of the Biomass Energy Department at CENER for their kind hospitality during this period. The CB2G infrastructure at CENER has been co-funded through the ERDF Funds, the Ministry of Economy and Competitiveness and the Government of Navarra. The Fortum Foundation and the Johan Gadolin Scholarship are also acknowledged for financial support in this study.

References

- [1] van Loo Sjaak, Koppejan Jaap. *Handbook of biomass combustion and co-firing*. Enschede: Twente University Press; 2002. p. 173–208.
- [2] Wilén C, Jukola P, Järvinen T, Sipilä K, Verhoeff F, Kiel J. Wood torrefaction – pilot tests and utilisation prospects. Espoo, VTT technology report 122; 2013. p. 73.
- [3] Järvinen T, Agar D. Experimentally determined storage and handling properties of fuel pellets made from torrefied whole-tree pine chips, logging residues and beech stem wood. *Fuel* 2014;129:330–9.
- [4] Agar D, Wihersaari M. Torrefaction technology for solid fuel production – a move towards greater sustainability. *Global Change Biol Bioenergy* 2011; 4:475–8.
- [5] Agar D, Wihersaari M. Bio-coal, torrefied lignocellulosic resources – key properties for its use in co-firing with fossil coal – their status. *Biomass Bioenergy* 2012;44:107–11.
- [6] Ericsson K, Nilsson LJ. Assessment of the potential biomass supply in Europe using a resource-focused approach. *Biomass Bioenergy* 2006;30:1–15.
- [7] Lehtikangas P. Quality properties of pelletised sawdust, logging residues and bark. *Biomass Bioenergy* 2001;20:351–60.
- [8] Sathre R, Gustavsson L. Time-dependent climate benefits of using forest residues to substitute fossil fuels. *Biomass Bioenergy* 2011;35:2506–16.
- [9] Guest G, Cherubini F, Stromman AH. Climate impact potential of utilizing forest residues for bioenergy in Norway. *Mitigat Adapt Strategy Global Clim* 2013;18:1089–108.
- [10] Directive 2009/28/EC of the European Parliament and of the Council. Official journal of the European Union; 2009.
- [11] Magelli F et al. An environmental impact assessment of exported wood pellets from Canada to Europe. *Biomass Bioenergy* 2009;33:434–41.
- [12] Lindholm EL, Berg S, Hansson PA. Energy efficiency and the environmental impact of harvesting stumps and logging residues. *Eur J For Resour* 2010; 129:1223–35.
- [13] Kabir MR, Kumar A. Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways. *Bioresour Technol* 2012;124:394–405.
- [14] Bergman PCA. Combined torrefaction and pelletisation – the TOP process. ECN-C-05-073. Petten, NL: Energy Research Centre of the Netherlands; 2005.
- [15] Larsson SH, Rudolfsson M, Nordwaeger M, Olofsson I, Samuelsson R. Effects of moisture content, torrefaction temperature, and die temperature in pilot scale pelletizing of torrefied Norway spruce. *Appl Energy* 2013;102:827–32.
- [16] Celaya J, Goni I, Gil J, Echeverría I. New pilot plant for biomass torrefaction. Biomass Energy Department, CENER – National Renewable Energy Centre. In: 18th European biomass conference and exhibition; 2010. p. 1544–9.
- [17] Di Blasi C, Lanzetta M. Intrinsic kinetics of isothermal xylan degradation in inert atmosphere. *J Anal Appl Pyrol* 1997;40–41:287–303.
- [18] European Commission Report. On sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling, SEC (2010) 65 & SEC (2010) 66; 2010.
- [19] Nurminen F. Environmental impacts of torrefied wood pellet production – case Rislog and Pursiala pilot plant, Mikkel, Miktech Oy report 7; 2013. p. 73.
- [20] Hakkila P. Developing technologies for large-scale production of forest chips, Sipoo, Wood Energy Technology Programme, VTT Technology report 6; 2004. p. 84.
- [21] Alakangas E. Properties of wood fuels used in Finland – BIOSOUTH project report, Jyväskylä; 2005. p. 90.
- [22] Wihersaari M. Greenhouse gas emissions from final harvest fuel chip production in Finland. *Biomass Bioenergy* 2005;28:435–43.
- [23] Wihersaari M. Evaluation of greenhouse gas emission risks from storage of wood residue. *Biomass Bioenergy* 2005;28:444–53.
- [24] EN 14918:2009 Solid biofuels – determination of calorific value.
- [25] Thek G, Obernberger I. Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. *Biomass Bioenergy* 2004; 27:671–93.
- [26] Nylund NO, Erkkila K. Heavy-duty truck emissions and fuel consumption. In: DEER conference, Chicago; 2005.
- [27] Michaelowa A, Krause K. International maritime transport and climate policy. *Intereconomics* May/June; 2000.
- [28] International Port-to-port shipping distances. <<http://www.searates.com/reference/portdistance/>>.
- [29] Royo J, Sebastián F, García-Galindo D, Gómez M, Díaz M. Large-scale analysis of GHG (greenhouse gas) reduction by means of biomass co-firing at country-scale: application to the Spanish case. *Energy* 2012;48:255–67.
- [30] Phanphanich M, Mani S. Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresour Technol* 2011;102:1246–53.
- [31] Repellin V, Govin A, Rolland M, Guyonnet R. Energy requirement for fine grinding of torrefied wood. *Biomass Bioenergy* 2010;34:923–30.
- [32] El-Wakil MM. *Powerplant technology*. International ed. Singapore: McGraw-Hill Inc.; 1984. p. 128–40.
- [33] Anttila M. Biohiilipellettien ja hiilen jauhatusta yhteispolttokokeet 0.5 MW:n pölypolttolaitteistossa, Biohiiliseminaari (Wood Torrefaction Workshop), Espoo, Finland, November; 2012.
- [34] Esteban LS, Carrasco JE. Evaluation of different strategies for pulverization of forest biomasses. *Powder Technol* 2006;166:139–51.
- [35] Temmerman M, Jensen PD, Hébert J. Von Rittinger theory adapted to wood chip and pellet milling in a laboratory scale hammer mill. *Biomass Bioenergy* 2013;56:70–81.